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Improving strategic noise mapping of railway noise in Europe: Refining CNOSSOS-EU calculations using TWINS

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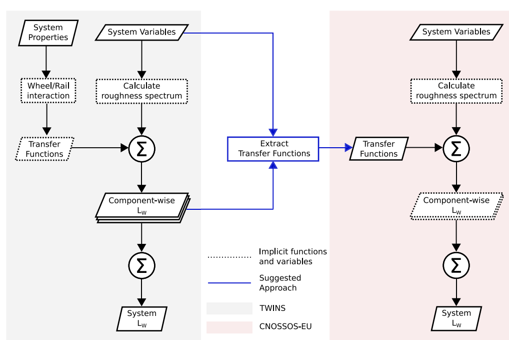
HIGHLIGHTS

- Improve the accuracy of railway noise calculation in the common noise assessment framework for Europe (CNOSSOS-EU)
- Extend the CNOSSOS-EU database of transfer functions with TWINS calculations
- Validate railway rolling noise calculations against results from TWINS
- TWINS Highlight key mitigation measures for reduced rolling noise emissions

GRAPHICAL ABSTRACT



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ABSTRACT

The Environmental Noise Directive (2002/49/EC) requires all European Union Member States to produce strategic noise maps using a common assessment methodology: CNOSSOS-EU. The reliability of CNOSSOS-EU railway noise evaluation is dependent on the input vehicle and track transfer functions. The CNOSSOS-EU default database contains the currently available choices for these transfer functions. However, these available transfer functions are limited and of insufficient quality, resulting in large errors in noise level calculations. An approach is presented, introducing an established analytical railway rolling noise calculation technique (TWINS), to extract more reliable and specific transfer functions. A case study consisting of railway rolling noise mitigation measures is defined and used as the basis for extracting and testing these transfer functions. The extracted transfer functions reduce the average deviation between CNOSSOS-EU and reference calculations using TWINS from 6.1 dB(A) to 0.8 dB(A) in absolute sound power levels, and from 1.2 db(A) to 0.3 dB(A) in estimates of noise reduction potential for the defined mitigation measures. Application of this approach shows potential to improve the quality and depth of the existing CNOSSOS-EU default database. This may lead to more reliable estimations of railway noise in the strategic noise maps and the subsequent assessment of its harmful effects.

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1. Introduction

Environmental noise was highlighted in Europe as a persistent environmental problem in the Green paper on Future Noise Policy in 1996 (C. of the European Communities, 1996), and has continued to grow as a major environmental stressor since. To address this growing problem, the Environmental Noise Directive (END) was established in 2002 (Directive, 2002). Since its introduction, this directive requires the European Union (EU) Member States (MS) to use harmonized noise indicators (i.e., L_{den} and L_{night}) for the assessment and management of environmental noise. The major sources of environmental noise are considered to be road, rail and air transport, and sites of industrial activity. The END also requires EU MS to prepare strategic noise maps every five years and consequently develop appropriate action plans. These common requirements, i.e., a periodic noise mapping using harmonized indicators, provide a common metric for all MS to address their noise pollution problem. This led to an increase in activity and importance within the area of strategic noise mapping (King and Rice, 2009; Murphy and King, 2014).

An update to the assessment methods for the noise indicators (Annex II of the END) was introduced in 2015 (Directive and Commission directive (eu), 2015), which enforced a change to the procedure for strategic noise mapping. Prior to the update, EU MS could calculate noise maps using their own choice of noise calculation tools. Following the update, all MS are required to use Common Noise Assessment Methods for Europe (CNOSSOS-EU) (Kephalopoulos et al., 2012) for calculating the strategic noise maps, starting from 31st December 2018. CNOSSOS-EU is a European calculation method which was created as a replacement for the contemporary noise calculation tools used by the MS. The motivation for this change, evident from the name of the method, was to further harmonize the noise evaluation efforts across EU. The 2015 update to Annex II specified many changes to the noise calculation procedure. Since this Annex forms the basis for performing a CNOSSOS-EU calculation, all these changes are implicitly accounted for in the resulting CNOSSOS-EU output included in the present contribution. The Annex II deadline requires all MS to have adopted CNOSSOS-EU for the 2022 round of strategic noise mapping, at the latest.

To facilitate this transition, CNOSSOS-EU includes a database of default values for its prerequisite parameters. This database enables prompt utilization of CNOSSOS-EU for noise source strength calculations. Furthermore, an interim solution has been provided for the case of railway noise (Paviotti et al., 2015), with the expectation that MS will progressively develop their own repository of parameter values.

However, early attempts to compare CNOSSOS-EU results with existing noise calculation tools present obstacles. This is particularly true for the case of railway noise, wherein CNOSSOS-EU calculations have overestimated noise levels, in comparison to existing tools, by up to 5 dB in Wosniacki and Zannin (2021) and 10 dB in Ögren and Ryberg (2015). For the case of railway noise, the root cause of the problem is that the rolling noise source strength model in CNOSSOS-EU is based on a semi-empirical approach, whereas most of the existing calculation techniques are fully empirical. Examples of the latter are the CRN approach in the UK (D. of Transport, 1995), the RMR in The Netherlands (van Volkshuisvesting, 1996) or the NMT96 in Sweden (Naturvårdsverket, 1999). This fundamental difference in the methodologies gives rise to two challenges during the transition to CNOSSOS-EU: *i)* existing source data cannot be directly reused, and *ii)* new types of data are required. Since rolling noise is usually considered as the most important source of noise from railways (Thompson, 2008), especially at conventional speeds, immediate consideration is required for overcoming these obstacles.

The overall CNOSSOS-EU railway noise calculation methodology includes two independent steps: *i)* vehicle noise source strength evaluation, and *ii)* noise propagation from source to receiver. The presented contribution focusses on step *i)*, in particular, on the assessment of rolling noise source strength. Step *ii)* is not implemented since the noise levels at a receiver position is not required within the scope of this contribution. Furthermore, the selective implementation of step *i)* allows for an evaluation which is independent of external errors such as from step *ii)*.

Two types of data are required for evaluating railway rolling noise in CNOSSOS-EU, which are not necessary for the fully empirical methods. The first type is related to the surface roughness of the wheel and rail. This data type is sensitive to the particular vehicle type and the track location. Input for this parameter is not easily available (Kephalopoulos et al., 2014) and it relies either on measurement campaigns, or on the default values available in CNOSSOS-EU. The second type of data is a transfer function (TF) for the vehicle or track component. The TF of a component quantifies its acoustic characteristics, and can be considered to be as important as the roughness data. Calculating a custom TF for a vehicle or track infrastructure in use in a country is not straightforward due to its analytical definition, especially when compared to the procedure when using fully-empirical techniques. Furthermore, the existing database of TFs only contain a generalized classification of vehicle and track infrastructures. This broad generalization can lead to having distinct railway infrastructures come under a common classification with identical noise emissions. The latest update to the END Annex II in 2021 (Commission delegated directive (eu), 2021), motivated by the necessity to accommodate recent technical and scientific progress, has led to changes to the existing CNOSSOS-EU database. Alongside modifications to the source definitions of existing infrastructure (e.g., impact and bridge noise), this update includes a new track category.

CNOSSOS-EU was introduced with the purpose of establishing a common platform for noise evaluations across EU. However, the challenges in using CNOSSOS-EU (especially for railway noise) may limit the expected accuracy of the resulting strategic noise maps, starting with the 2022 round of strategic noise mapping. An effective step in improving CNOSSOS-EU is to expand its database with reliable TFs which correspond to more specific classes of vehicle or track infrastructure. These new TFs are intended to make noise mapping with CNOSSOS-EU more reliable for estimating population noise exposure, and evaluating subsequent noise action plans. Another benefit of the improved noise estimation would be in the assessment of the harmful effects of environmental noise on the population (Eriksson et al., 2017; Commission directive (eu), 2020; Faulkner and Murphy, 2022).

The objective of this contribution is to generate TFs in order to further develop the size and quality of the CNOSSOS-EU database. To achieve this, the approach introduces calculations made by an analytical railway rolling noise calculation technique – TWINS (Track-Wheel Interaction Noise Software) (Thompson et al., 1996a; Thompson et al., 1996b). Using TWINS for this task is in line with suggestions made by the developers of CNOSSOS-EU (Paviotti et al., 2015). A case study is defined for applying and testing this approach. This case study considers various rolling noise mitigation measures which are applicable to a baseline railway infrastructure typical for freight wagons in Sweden.

2. Methodology

In the proposed approach, TWINS was used to extract suitable transfer functions (TFs) for CNOSSOS-EU. TWINS was chosen because of its capacity to estimate rolling noise within 2 dB of that from measurements (Jones and Thompson, 2003; Kitagawa and Thompson, 2006), an accuracy better than that of CNOSSOS-EU (Ögren and Ryberg, 2015; Kokkonen et al., 2016). This made TWINS a suitable target for CNOSSOS-EU to emulate. Furthermore, TWINS and CNOSSOS-EU have similarities in the calculation framework, thereby enabling comparisons at intermediate steps.

The extraction of a TF for a particular railway infrastructure requires the output sound power level (SWL) from TWINS for that particular component (i.e., SWL of the wheel, rail or sleeper) and the system's total roughness. A similar approach was presented in (Thompson, 1996) where sound pressure levels were used instead of sound power levels. The presented approach was confined to sound power levels in order to remove sensitivity to differences in noise propagation calculations. Verification of this extracted TF was possible, provided there were CNOSSOS-EU and TWINS results corresponding to the same railway infrastructure. A flowchart of the methodology is shown in Fig. 1.

2.1. Extracting transfer functions

The extraction of TFs from TWINS calculations for a particular CNOSSOS-EU component involved the following two steps: first, obtain the input roughness spectrum in the frequency domain; and second, calculate the TF as the difference between the SWL of the corresponding TWINS components and the input roughness spectra in $1/3^{rd}$ octave bands. These two steps are further detailed below.

The procedure to calculate the input excitation spectrum was based on the procedure followed by the CNOSSOS-EU railway noise calculation method (Section IV.2.2.1 in Kephalopoulos et al., 2012). The calculated spectrum was implicit in the CNOSSOS-EU calculation scheme, and was therefore not directly available. Since the extraction of TFs required this spectrum, it had to be explicitly calculated according to the steps in Section 2.1.1.

2.1.1. Calculating input excitation spectrum

The input excitation for railway rolling noise is defined by the roughness spectrum in the frequency domain. This spectrum is converted from the wavenumber domain, where roughness is physically measured, to the frequency domain according to the vehicle speed.

The roughness spectrum in the wavenumber domain is obtained by the energetic addition of the rail and wheel roughness spectra, along with a logarithmic penalty on the shorter wavelengths which is defined by the Contact Filter (CF) (Kephalopoulos et al., 2012). It may be written as

$$L_{R,\text{Total},\lambda_i} = 10\ \log\left(10^{L_{R,\text{Wheel},\lambda_i}/10} + 10^{L_{R,\text{Rail},\lambda_i}/10}\right) + \text{CF}_{\lambda_i}, \tag{1}$$

where $L_{R,Wheel,\ \lambda i}$ and $L_{R,Rail,\ \lambda i}$ are the wheel and rail roughness values in dB, for wavenumber band λ_i; $\text{CF}_{\lambda i}$ is the contact filter penalty defined by the axle load and wheel diameter, for wavenumber band λ_i.

Each wavenumber band λ_i in the roughness spectrum is mapped to a corresponding frequency band f_i', such that

$$L_{R,\text{Total},f_i'} = L_{R,\text{Total},\lambda_i}, \tag{2}$$

given that the vehicle speed *vs* links the roughness at a wavenumber band λ_i to its corresponding frequency band f_i' according to the relation

$$f_i' = v/\lambda_i. \tag{3}$$

Since the resulting frequency bands shift along the frequency range for varying vehicle speeds, these frequency bands $\{f_i'\}$ do not necessarily correspond to the standard definitions of $1/3^{rd}$ octave bands $\{f_i\}$.

$L_{R,\ \text{Total},\ fi}$ denotes the input roughness for a particular standard $1/3^{rd}$ octave band f_i. It is obtained by energetically and proportionally adding the frequency bands of $L_{R,\ Total,\ fi'}$ that overlap with f_i (Kephalopoulos et al., 2012). $L_{R,\ \text{Total},\ fi}$ may thus be calculated as

$$L_{R,\text{Total},f_i} = 10\ \log\left(\sum_{f_j'}^{\{f_j'\}} \chi_{f_i,f_j'} * 10^{L_{R,\text{Total},f_j'}/10}\right), \tag{4}$$

where $\chi_{fi,\ fj'}$ is the fractional overlap in the frequency domain between band f_i and f_j'. $\chi_{fi,\ fj'}$ is defined as

$$\chi_{f_i,f_j'} = \begin{cases} 0 & \text{if } f_i \cap f_j' = \varnothing \\ \dfrac{\min\left(f_{j,b}', f_{i,b}\right) - \max\left(f_{j,a}', f_{i,a}\right)}{f_{j,b}' - f_{j,a}'} & \text{if } f_i \cap f_j' \neq \varnothing \end{cases}, \tag{5}$$

where the subscripts *a* and *b* denote the lower and upper limits of a $1/3^{rd}$ octave band, respectively. The correctness of Eqs. (4) and (5) was verified by choosing a $L_{R,\text{Total},\ \lambda i}$ and v, and comparing the calculated $L_{R,\text{Total},\ \text{fi}}$ with the corresponding output from a CNOSSOS-EU calculation with empty transfer functions.

2.1.2. Processing TWINS calculations

The TFs for CNOSSOS-EU were extracted from component-wise sound power levels obtained from TWINS calculations. Each TWINS calculation

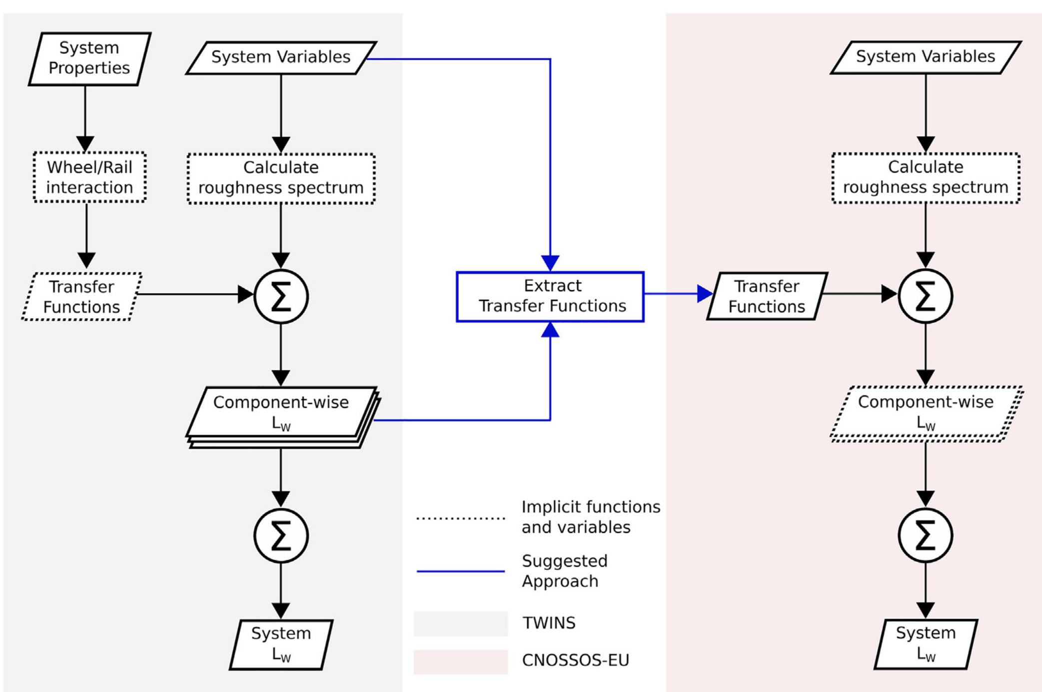

Fig. 1. Flowchart of the approach to extract transfer functions for CNOSSOS-EU from TWINS calculations. L_W denotes sound power levels.

contained SWLs for three components, and therefore yielded three distinct transfer functions which were specific to the specifications of each component (e.g., material and geometrical properties).

The TF was extracted as

$$\mathrm{TF}_{\mathrm{comp},\mathrm{f_i}} = L_{W,\mathrm{comp},\mathrm{f_i}} - L_{R,\mathrm{Total},\mathrm{f_i}}, \tag{6}$$

where comp ∈ {wheel, rail, sleeper}, f_i is the $1/3^{rd}$ octave band, L_W is the SWL calculated by TWINS, L_R is the input excitation spectrum calculated using Eq. (4).

TFs corresponding to the same component specification can be extracted from multiple distinct TWINS calculations (all of which contain this component specification), but they may not be identical as expected. An example of this is illustrated in the case study of Section 4.2, in Figs. 9 and 10. The cause for this observed variability is assumed to be due to the wheel-rail interaction model in TWINS, since it allows for a coupling between the different components (Thompson et al., 1996a). The CNOSSOS-EU methodology assumes that the contribution associated with each component is independent of the properties of the other components. Therefore, in order to calculate TFs suited for the assumptions of CNOSSOS-EU, the extracted TFs corresponding to the same component specification were averaged, thus reducing the impact of this coupling, such that

$$\mathrm{TF}_{comp,f_i} = \frac{\sum_{j=1}^{N} \mathrm{TF}^{j}_{comp,f_i}}{N}, \tag{7}$$

where TF^j is the j^{th} extracted TF for a component from a total of N such TFs corresponding to the same component specification.

It is to be noted that the frequency spectrum of an extracted TF is limited to the output spectrum of TWINS which corresponds to the range 100 Hz–5 kHz. Therefore, to be usable by CNOSSOS-EU (with frequency spectrum ranging from 63 Hz–10 kHz) the extracted TF was extrapolated assuming a zero-order extrapolation (i.e., missing values set to the nearest known value).

2.2. Verifying transfer functions with TWINS

TWINS, being an analytical railway rolling noise calculation technique (Thompson et al., 1996a; Thompson et al., 1996b), is based on the same rolling noise calculation framework as CNOSSOS-EU. This common framework implies that both calculations, when provided with identical input, are expected to give similar output. This justifies the suggestion by the developers of CNOSSOS-EU to use TWINS as a source for its input TFs (Extrium, 2015). Additionally, this principle also allows to verify these extracted TFs. The verification was done by comparing CNOSSOS-EU rolling noise estimations (made using the extracted TFs) with those from TWINS.

The default unit of the CNOSSOS-EU output $L_{W'}$ (SWL per meter (Kephalopoulos et al., 2012)) required conversion to match that of TWINS (SWL per wheel and associated rail vibration (Thompson et al., 1996a)). An intermediate unit within the CNOSSOS-EU calculation scheme is rolling noise SWL per axle, and this was assumed to be equivalent to the output unit calculated by TWINS.

Similar to the input excitation spectrum, the CNOSSOS-EU output in this intermediate unit is not directly available and requires explicit calculation. This was done in this contribution by a rearrangement of the implicit conversion found in Eq. (IV-2) and Eqs. (IV-7,8,9) in (Kephalopoulos et al., 2012), such that

$$L_W = L_{W'} - 10 \log\left(\frac{Q^* N_a}{1000^* v}\right), \tag{8}$$

where Q is the vehicle volume flow rate in railway wagons per hour, N_a is the number of axles per wagon and v is the vehicle speed in km h^{-1}.

The output from TWINS and CNOSSOS-EU for a particular train-track configuration was compared using two metrics. The first was an absolute metric which in this case was the SWL calculated for a particular configuration. The second was a relative metric, ΔL_W, corresponding to the difference between the SWL of a particular configuration and the SWL of a chosen baseline configuration. These metrics were chosen for their physical significance: the absolute metric quantifies the rolling noise potential of a train-track configuration, whereas the relative metric quantifies the noise-reducing potential of a particular configuration over the baseline.

3. Case study: comparison of rolling noise mitigation measures

A case study was introduced in order to evaluate the proposed approach, comparing the calculation results from TWINS with those from CNOSSOS-EU when using extracted TFs.

The case study consisted of eight cases, each corresponding to a distinct train-track configuration. The first case was used as a reference, and represents the baseline configuration. Its configuration was defined to represent a freight wagon on a railway track typically found in Sweden. The other seven cases implemented one or two mitigation measures to the baseline configuration. The mitigation measures chosen for this case study were:

(i) Changing brake type from Cast-Iron to Disc brakes
(ii) Grinding the rail head
(iii) Stiffening the rail pads (from soft to hard rail pads)
(iv) Installing rail dampers

The definition of the test cases is shown in Table 1. The first measure (i.e., change in brake type) was considered as a primary measure. The other three measures, considered as secondary measures, were implemented either independently or in combination with the primary measure. This implied that there were a total of eight unique configurations: one with no measure (baseline), one with only the primary measure, three with only a secondary measure, and three with both the primary and a secondary measure. The primary measure involved a modification to the wheel component, whereas all the secondary measures targeted the track component.

For this case study, TWINS calculation results were utilized for two purposes: first, as an input to the approach for extracting TFs for CNOSSOS-EU (Eq. (6)); and second, to evaluate the approach by a comparison with output from CNOSSOS-EU calculations. The TWINS calculations for the cases considered were obtained from (Venkataraman et al., 2019; Toward, 2019). It is to be noted that the calculations in these technical reports were performed prior to the 2021 update to END Annex II (Commission delegated directive (eu), Jul 2021) which brought a change to the definition of the chosen contact filter. The frequency independence of TWINS and CNOSSOS-EU calculations across the octave bands allowed for implementing the effect of this change on the resulting SWL spectrum after appropriate transformation from the wavenumber to the frequency domain.

3.1. Baseline configuration

The baseline train-track configuration was defined to represent a freight wagon running on a railway track in Sweden. In this baseline configuration, a freight wagon was assumed to be equipped with 920 mm-diameter wheels equipped with cast-iron block brakes. The track was assumed to be a mono-block sleeper with soft rail pads. For the rail roughness, a railway

Table 1
Definition of the test cases. For a particular case: 'Y' denotes a measure that was implemented, and '–' for a measure that was ignored. Case 1 represents the baseline configuration.

Case	Change brake type (primary)	Grind rail head (secondary)	Stiffen rail pads (secondary)	Install rail dampers (secondary)
1	–	–	–	–
2	Y	–	–	–
3	–	Y	–	–
4	Y	Y	–	–
5	–	–	Y	–
6	Y	–	Y	–
7	–	–	–	Y
8	Y	–	–	Y

track in Järna, Sweden, was assumed to be a representative track; hence the roughness measurements taken at this track (obtained from (Nielsen, 2009)) were used as the input rail roughness spectrum. The wagons were assumed to have an axle load of 100 kN, and run at 80 km h^{-1}.

The format of the input data and the level of detail when specifying a train-track configuration were not identical for CNOSSOS-EU and TWINS. Only the roughness spectra of rail, wheel and contact filter, and the vehicle speed were specified using the same format for both methodologies (although CNOSSOS-EU required a wider roughness spectra). All other parameters were specified through different formats: geometric models and material properties for TWINS, and transfer functions for CNOSSOS-EU.

Table 2 lists the specifications of the baseline configuration. In this table, the configuration specifications were first classified by their corresponding component (wheel or track), and then listed as features of that component.

3.2. Changing brake type

The primary mitigation measure in this case study was a change in the brake type of the freight wagon; a switch from Cast-iron block brakes to Disc brakes. Such a change in the brake system showed potential to reduce railway noise by up to 14 dB(A) (Hölzl, 1996) and could be considered as a first step to reduce railway rolling noise (Dings and Dittrich, 1996). This change in technology affected the following two features of the wheel that contribute to rolling noise:

1. Change in wheel roughness - Cast-Iron block braked wheels possess a greater wheel roughness when compared to Disc braked wheels due to the direct contact of the brake blocks with the wheel tread. Fig. 2 compares the roughness spectra for the two types of wheel, obtained from (Squicciarini et al., 2015). These measurements were extrapolated as shown in the figure to satisfy the roughness spectrum requirements in CNOSSOS-EU. The wheel roughness spectra in Fig. 2 was taken as input to both CNOSSOS-EU and TWINS. The SWL calculated using CNOSSOS-EU was less sensitive to the roughness values at the extrapolated wavelengths. This was due to the attenuating effect of the contact filter (for short wavelengths) and the A-weighting filter (for both short and long wavelengths).
2. Change in wheel geometry - Cast-Iron braked wheels have a curved web compared to the straight web of Disc braked wheels. The geometry of the wheel profile affects its strength as a rolling noise source, with source strength considered to be proportional to the surface area of the wheel. In TWINS, this change was implemented through the use of a different wheel geometry model for each brake type. In CNOSSOS-EU, the same implementation required using different vehicle TFs. However, the CNOSSOS-EU default database available at the time of calculation did not have wheel-geometry specific vehicle TFs. Therefore, the change in wheel geometry was not implemented in the default calculation. This issue was here overcome by using the presented approach to extract specific TFs from TWINS calculations. A comparison of the resulting brake-type dependent vehicle TFs is presented in Section 4.2.

Table 2
Specifications of the baseline configuration representing a typical freight wagon on Swedish railway network. * and † denote features represented in CNOSSOS-EU by the vehicle TF and track TF, respectively. ‡ denote features geometrically modelled in TWINS.

Component	Feature	Parameter value	
		TWINS	CNOSSOS-EU
Wheel	Geometry*	BA308 Curved Web, 920 mm wheel diameter‡	920 mm wheel diameter, no measure (Fig. 8)
	Roughness	Cast Iron brake wheel roughness (Squicciarini et al., 2015) (Fig. 2)	
	Contact Filter	Axle load 100 kN, 920 mm wheel diameter ()	
Track	Rail type†	UIC-60‡	Mono-block sleeper on soft rail pad, no measure (Figs. 9 and 10)
	Sleeper†	Concrete mono-block‡	
	Rail pad†	Pandol soft studded 10 mm rail pads‡	
	Damper†	Absent	
	Ballast	Granite	–
	Rail roughness	Medium rail - Jarna2 (Nielsen, 2009) (Fig. 3)	

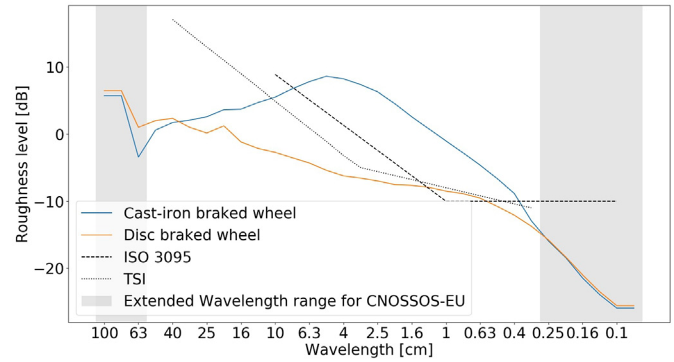

Fig. 2. Typical wheel roughness spectra for Cast-iron and Disc braked technologies obtained from Squicciarini et al. (2015) and plotted in comparison with ISO 3095 (ISO, 2005) and TSI limits (TSI, 2014).

3.3. Rail grinding

Rail grinding was considered as a secondary measure to supplement the reduction in wheel roughness produced by the primary measure (i.e., changing the brake type). This choice was based on the knowledge that rolling noise is strongly influenced by both the brake type as well as the condition of the rail surface (Hölzl, 1996). Since the combined roughness of the train-track system is the energetic addition of rail and wheel roughness levels (see Eq. (1)), a reduction in wheel roughness may have a negligible impact on the combined roughness if the rail roughness is sufficiently large; see the impact of brake change on combined roughness for the Medium rail in Fig. 4. To avoid this, rail grinding was introduced as a complementary secondary measure in order to effectively capture the reduction in wheel roughness levels produced by the primary measure.

A "smooth" rail roughness spectrum was defined to quantify the effect of rail grinding on the baseline rail roughness. The choice of the baseline rail roughness spectrum, denoted as the "medium" rail, was based on roughness measurements performed at the previously mentioned rail track in Järna, Sweden (taken from Nielsen, 2009). Likewise, the smooth rail was obtained from measurements performed at Gärsdjö, a track which had undergone rail grinding shortly before the measurements.

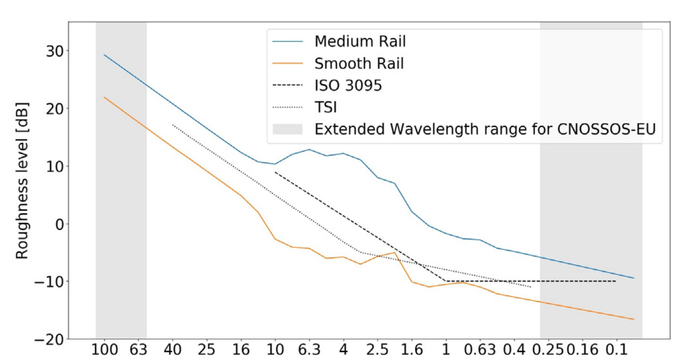

Fig. 3. Rail roughness spectra of Järna2 (medium roughness) and Gärdsjö (smooth roughness) obtained from Nielsen (2009) and extrapolated, shown in comparison with ISO 3095 (ISO, 2005) and TSI limits (TSI, 2014).

The roughness spectra for these two rails are shown in Fig. 3. The measured wavelengths obtained from Nielsen (2009) spanned from 16 cm - 5 cm and is a subset of the requirements for TWINS and CNOSSOS-EU. A logarithmic extrapolation of the spectra was performed, corresponding to a constant change of +6.5 dB and −2 dB per octave for the longer and shorter wavelengths, respectively. Since both calculation schemes took the same input roughness, the choice of extrapolation did not affect the extraction nor testing of TFs. The rail roughness spectra in Fig. 3 was taken as input to both CNOSSOS-EU and TWINS.

3.4. Rail-pad stiffening

Stiffening of rail-pads was chosen as another secondary measure. This measure was chosen as an alternative approach to reduce the contribution of the rail component to rolling noise. This rail-noise reduction capability of rail-pads was noted in previous studies (Jiang et al., 2013).

The values for rail-pad vertical stiffness considered for this measure were based on the specifications of track TFs found in the default CNOSSOS-EU database (Kephalopoulos et al., 2012). The track in the baseline configuration was assumed to have "soft" rail pads with a vertical dynamic stiffness of 150 MN m^{-1}. The default database contained two other rail-pads with different stiffness values: "medium" rail-pads with a stiffness of 500 MN m^{-1}, and "hard" rail-pads with 1000 MN m^{-1}. The output SWLs for this measure were calculated considering both medium and hard rail-pads. For clarity, only the results for the hard rail-pads are presented.

In TWINS, this change was implemented by modifying the material properties of the rail-pad in the numerical model. In CNOSSOS-EU, rail-pad stiffness can only be implicitly defined through a track TF. Therefore, this measure was implemented by changing the track TF from the one for soft rail-pads to the one for hard rail-pads. The TFs for all three classes of rail-pads (soft, medium and hard) are presented in Section 4.2.

3.5. Installing rail-dampers

The installation of rail-dampers was the final secondary mitigation measure. It was described in Thompson and Gautier (2006) as an effective solution to reduce rail noise. This was another measure which reduces the rail-components contribution to rolling noise through an ad-hoc increase of the track decay rates.

In TWINS it was possible to override the numerical model's track decay rates by providing measured values. This functionality enabled implementing the installation of a rail-damper. Tata Steel rail-dampers were considered (Toward, 2019), and measurements of track decay rates before and after installation were provided as input to TWINS; see Fig. 5.

In CNOSSOS-EU, similar to the problem with implementing different wheel geometries, calculating the impact of rail-dampers was not possible

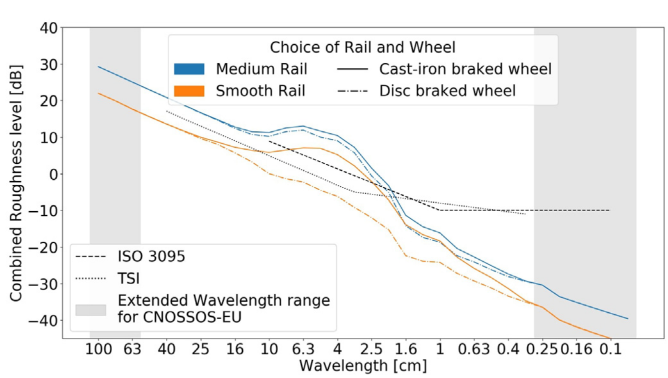

Fig. 4. Combined roughness of the wheel (Fig. 2), rail (Fig. 3) and Contact filter (from Commission delegated directive (eu), Jul 2021) for the four wheel-rail combinations, shown in comparison with ISO 3095 (ISO, 2005) and TSI limits (TSI, 2014).

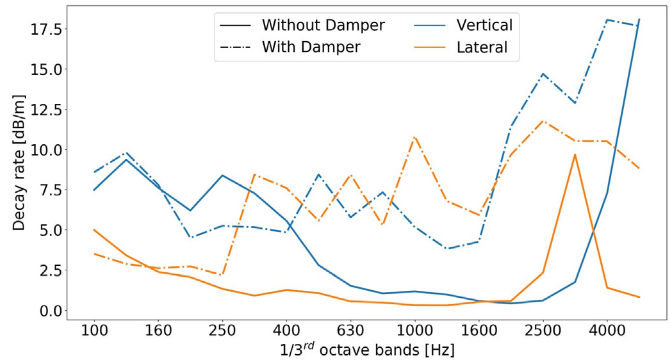

Fig. 5. Rail decay rates taken as input by TWINS for modelling the impact of rail-dampers.

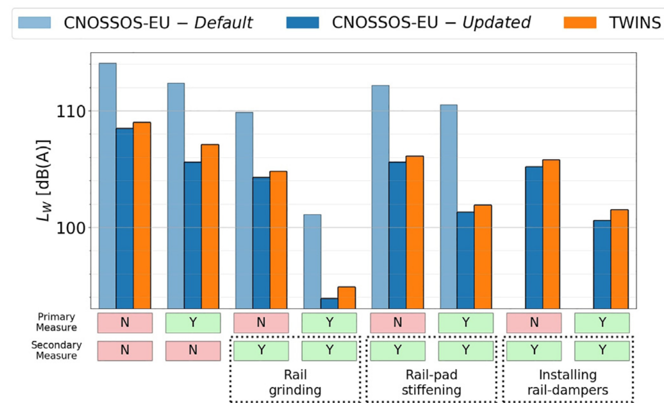

Fig. 6. Comparison of the absolute rolling noise SWL calculations for all cases considered (see Table 1), using CNOSSOS-EU and TWINS. The first train-track configuration represents the baseline; the second implements only the primary measure; all subsequent cases implement a secondary measure either independently or in combination with the primary measure.

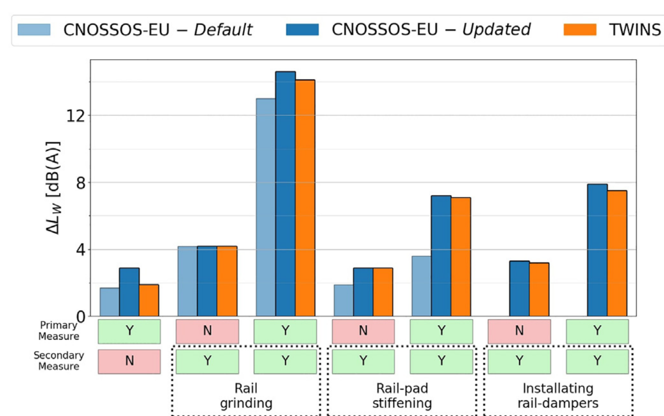

Fig. 7. Comparison of the relative reduction in SWL with reference to the baseline configuration (i.e., first configuration in Fig. 6), using CNOSSOS-EU and TWINS.

since relevant track TFs were not available in the CNOSSOS-EU default database available at the time of calculation. The presented approach of extracting TFs from TWINS was used to overcome this problem, and the results are presented in Section 4.

4. Results and discussion

Rolling noise SWLs were evaluated using the TWINS calculation for the case study of train-track configurations defined in Section 3. New TFs were

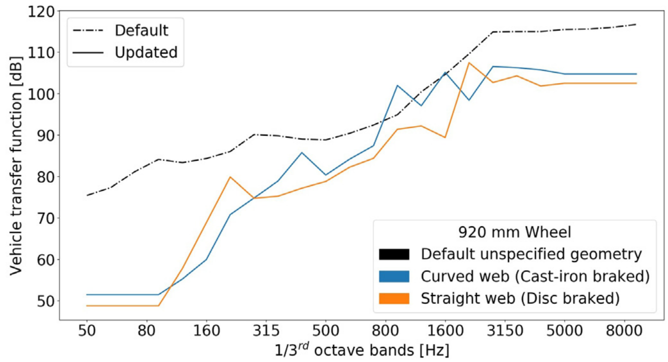

Fig. 8. Default and extracted vehicle TFs for a 920 mm diameter wheel.

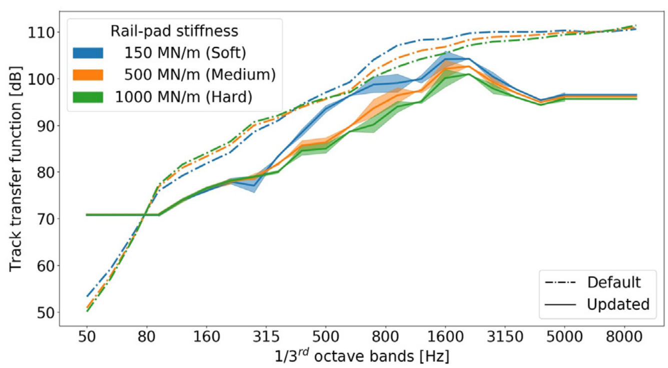

Fig. 9. Default and extracted track TFs for a mono-block sleeper on three type of rail pads - Soft, Medium and Hard. Shaded region denotes the variation of an extracted TF when obtained from different configurations.

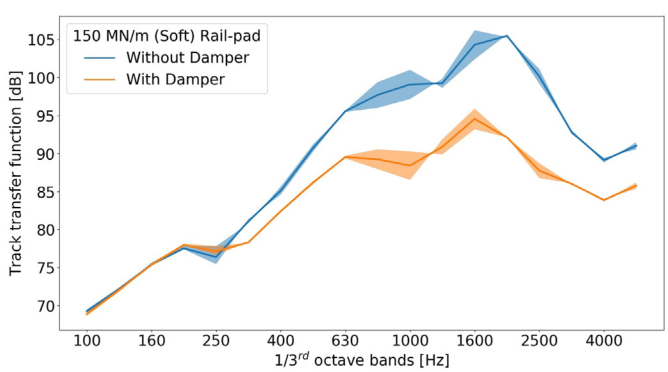

Fig. 10. Extracted track TFs for mono-block sleeper on soft rail-pads, with and without rail-dampers. Shaded region denotes the variation of an extracted TF when obtained from different configurations.

extracted using the output from the TWINS calculation, following the approach presented in Section 2. Two sets of CNOSSOS-EU calculations were performed with different wheel and track TFs. They were defined as follows:

- *Default* - Uses existing TFs from the CNOSSOS-EU database
- *Updated* - Uses TFs extracted from TWINS calculations

To quantify the improvement brought by these extracted TFs (and consequently the approach), these CNOSSOS-EU calculations were compared with that from TWINS.

The configurations in the case study differed by the presence of either one or two railway noise mitigation measures (Table 1). A measure was considered to be either the primary measure (i.e., change in brake type)

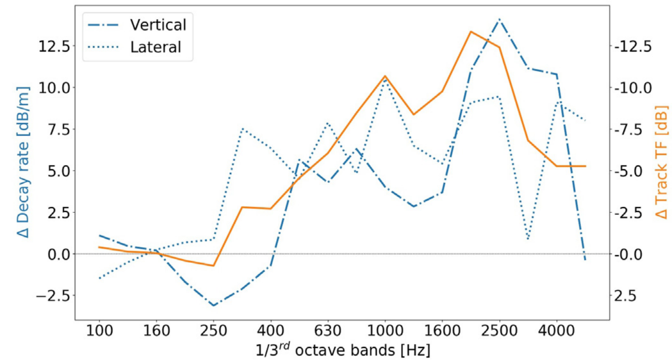

Fig. 11. Comparison of change in track decay rates with change in track TF due to installation of rail-dampers. Δ Decay rate calculated from Fig. 5, and Δ Track TF from Fig. 10.

or one of the three secondary measures (i.e., rail grinding, rail-pad stiffening, or installing rail-dampers).

The SWLs from CNOSSOS-EU and TWINS are compared in Section 4.1, and the different TFs used for the CNOSSOS-EU calculations are shown in Section 4.2. Note that, as previously mentioned in Section 2.2, the output from CNOSSOS-EU was transformed to a unit that enabled comparison with TWINS.

4.1. Comparison of sound power levels

The rolling noise SWLs for the train-track configurations defined in the case study (Table 1) are presented in Figs. 6 and 7. Fig. 6 compares these calculations using an absolute metric. Fig. 7 compares them using a relative metric, i.e., a reduction in SWL with reference to the baseline configuration.

Note that the *Default* CNOSSOS-EU calculation is not presented for the configurations for which it could not be evaluated (i.e., installation of rail-dampers, see Section 3.5). Consequently, the average levels associated with the *Default* calculation do not include these cases. When stating the difference between the results from CNOSSOS-EU and TWINS calculations, a '+' sign implies that the CNOSSOS-EU results were larger in magnitude.

4.1.1. Default CNOSSOS-EU and TWINS

Comparison of the absolute SWLs between the *Default* CNOSSOS-EU calculations and the TWINS calculations showed an average variation of +6.1 dB(A) with a maximum of 8.6 dB(A) (primary measure and rail-pad stiffening) and a minimum of +5.1 dB(A) (Cast-Iron braked wheels on soft rail pads); see Fig. 6. Using the relative metric, the average variation was −1.2 dB(A), with a maximum variation of −3.5 dB(A) (primary measure and rail-pad stiffening) and a minimum of 0 dB(A) (rail grinding); see Fig. 7. The variations showed a contrasting behaviour under the two metrics: the *Default* CNOSSOS-EU calculation estimated a larger SWL for the same train-track configuration (absolute metric), whereas it estimated a lower effectiveness of a particular mitigation measure (relative metric).

Given that the TWINS calculations are capable of estimating rolling noise within 2 dB from measurements (Jones and Thompson, 2003; Kitagawa and Thompson, 2006), the larger mean variations observed between the *Default* CNOSSOS-EU and TWINS calculations (6.1 dB(A) for absolute) imply that TWINS is assuredly the more accurate of the two. TWINS may therefore be justified as a suitable target for CNOSSOS-EU. The accuracy of CNOSSOS-EU SWL calculations may therefore be improved by attempting to replicate the results of TWINS.

The large variations between the *Default* CNOSSOS-EU and TWINS calculations for the different cases also reveal the limitations of the TFs in the default CNOSSOS-EU database. The overestimation of CNOSSOS-EU absolute SWLs may be caused by default TFs whose magnitudes are higher than they should be. This may also explain the underestimated reduction potentials of the mitigation measures. Given that the total SWL is a logarithmic addition of the vehicle and train component, the reduction obtained in one component will have a lesser impact on the total SWL, as the magnitude of the other component increases. This assertion is further considered when comparing the extracted and default TFs in Section 4.2.

Using the relative metric, the *Default* calculation matches the TWINS calculation for the following two cases: first with the primary measure (−0.2 dB(A) difference), and second with rail-grinding (0 dB (A) difference). For the first case (primary measure), the accurate estimation of the primary measure is considered to be a coincidence. The *Default* CNOSSOS-EU calculation, unlike the TWINS calculation, does not implement a noise-reducing change to the wheel geometry (see Section 3.2). Therefore, this CNOSSOS-EU calculation is expected to underestimate the reducing potential of this measure, and not coincidentally match it as seen in the comparison. For the second case (rail-grinding), the accurate estimation of rail-grinding (in the relative metric) may be explained by the simplistic implementation, i.e., a direct modification to the rail roughness spectrum. Within a frequency band, a change in dB in the combined roughness produces the same change in dB in its absolute SWL. Therefore, this type of measure produces comparable output in the relative metric, irrespective of differences in the absolute metric; compare rail-grinding in Figs. 6 and 7.

4.1.2. Default CNOSSOS-EU and Updated CNOSSOS-EU

The two sets of CNOSSOS-EU calculations were compared using the absolute and relative metrics. The absolute SWLs showed an average variation of 6.8 dB(A), with a maximum of 9.2 dB(A) (primary measure and rail-pad stiffening) and a minimum of 5.6 dB(A); see Fig. 6. For all configurations considered, the absolute SWLs from the *Default* calculation were larger in magnitude than that from the *Updated* calculation. In the case of the relative metric, the average variation was 1.5 dB(A), with a maximum of 3.6 dB (A) (primary measure and rail-pad stiffening) and a minimum of 0.0 dB (A) (rail grinding); see Fig. 7. In contrast to the trend observed using the absolute metric, the reductions in rolling noise SWLs were lower for the *Default* calculation than for the *Updated* calculation, when using the relative metric.

The large variations (up to 9.2 dB(A)) between the *Default* and *Updated* calculations imply that the default TFs (used for the former) are significantly different from the extracted TFs (used for the latter). This is an inference from the fact that these two calculations differ only by the choice of their vehicle and track TFs. Even the range of variations (5.6 dB(A) to 9.2 dB(A)) is large, implying that the offset between the default and extracted TFs is not a constant, but is dependent on the train-track configuration.

It is also worth noting that the *Updated* CNOSSOS-EU calculation is capable of evaluating train-track configurations (e.g., configurations with rail-dampers) that are beyond the scope of the *Default* calculation.

4.1.3. Updated CNOSSOS-EU and TWINS

The greatest similarity in SWLs was obtained when comparing the *Updated* CNOSSOS-EU calculations with those from TWINS. The absolute SWLs showed an average variation of 0.8 dB(A) with respect to TWINS, with a maximum of −1.5 dB(A) (primary measure) and a minimum of −0.5 dB(A); see Fig. 6. For all of these cases, absolute SWLs from the *Updated* calculation underestimated the rolling noise SWLs from TWINS. For the relative metric, the average deviation was +0.3 dB(A), with a maximum of +1 dB(A) (primary measure) and a minimum of 0.0 dB(A); see Fig. 7. Similar to the previous two comparisons (*Default* with TWINS and *Default* with *Updated*), an opposite trend in variations was observed between the absolute and relative metrics.

The good agreement between the *Updated* CNOSSOS-EU and TWINS calculations reflects the effectiveness of the extracted TFs. This consequently adds to the reliability of the presented approach for extracting TFs from TWINS calculations. The good agreement is also observed for train-track configurations that were beyond the scope of the *Default* calculation (i.e., configurations with rail-dampers). Therefore, not only does the presented approach show potential to improve the existing CNOSSOS-EU TFs, but it also enables generating new TFs that may be used to account for configurations outside the scope of the default database.

On the other hand, the *Updated* calculation shows the largest deviation for the case with the primary measure, with a difference of −1.5 dB(A) in absolute SWL and + 1 dB(A) in reduction potential. This may be attributed to a extracted track TF that is slightly underestimated. The difference with TWINS becomes more pronounced after implementing the primary measure since this measure only reduces the rolling noise contribution from the wheel, thereby making the CNOSSOS-EU output more sensitive to the track TF.

The most significant improvement in the output from the *Updated* calculation over the *Default* one is the overall reduction in the absolute SWLs. All the absolute SWLs from the *Updated* calculation are lower in magnitude by about 6.8 dB(A), resulting in a better match with the absolute levels from the TWINS calculation. This improvement may enable more accurate estimation of railway noise exposure when using CNOSSOS-EU, especially in the context of preparing END strategic noise maps.

A consequence of the improvement in the absolute metric is also seen in the relative metric (Fig. 7). This is especially noticeable for the cases that consider both the primary and secondary measures. For the cases with the secondary measure being rail grinding and rail-pad stiffening, the *Default* calculation underestimates the reduction potential by 1.1 dB(A) and 3.5 dB(A), respectively. In comparison, the *Updated* calculation estimates the reduction potential within 0.5 dB(A) of that from TWINS. This improvement in estimating the reduction potential of mitigation measures enables to define more realistic noise action plans when using CNOSSOS-EU, especially in the context of fulfilling the END requirements.

4.2. Comparison of transfer functions

Each CNOSSOS-EU calculation required one track TF and one vehicle TF to represent the train-track configuration. A TF was either obtained from the CNOSSOS-EU default database, or extracted using the proposed approach (Section 2) using TWINS calculations. The vehicle TFs, which quantify the rolling noise contribution from the wheel, are shown in Fig. 8. The track TFs, which quantify the contributions from the sleeper and the rail to rolling noise, are shown in Figs. 9 and 10.

4.2.1. Vehicle transfer functions

In the case study, implementing the primary measure (i.e., change in brake type) involved making two changes to the input parameters, the vehicle TF being one of them. This change in the vehicle TF was not implemented in the *Default* CNOSSOS-EU calculation due to limitations of the default database. Therefore, the *Default* calculation used only one vehicle TF, whereas the *Updated* calculation used two TFs: one for representing the baseline, and one for implementing the primary measure. These default and extracted vehicle TFs are shown in Fig. 8.

The default TF was found to be larger in magnitude than the extracted TFs for almost the entire spectrum; see Fig. 8. Upon comparison of the two extracted TFs, the TF associated with the curved web wheel was larger in magnitude than that of the straight web wheel for the greater portion of the spectrum.

The extraction of TFs from TWINS enables differentiating between two wheels of the same radius but with different web geometries. The higher magnitude of the TF for the curved web wheel is expected, given that the acoustic radiation of a wheel increases in proportion to its surface area. The validity of these TFs are further highlighted by the overall improvements in matching TWINS calculations seen in Figs. 6 and 7. Therefore, the approach proposed confirms to be a viable way to enrich the CNOSSOS-EU database with vehicle TFs which are more specific and accurate than those in the default database.

4.2.2. Track transfer functions

All the secondary mitigation measures chosen for the case study involved a change to the track infrastructure. Aside from rail grinding, which only involved a change to the roughness spectrum, rail-pad stiffening and installing rail-dampers was implemented through a modification to the track TF. For both of these mitigation measures, the track TFs used for the CNOSSOS-EU calculations are compared.

A track TF extracted from a TWINS calculation is dependent on the vehicle specifications due to the wheel-rail interaction model used by TWINS (Thompson et al., 1996a). Following the procedure in Section 2.1.2, the extracted TFs in Figs. 9 and 10 were obtained using Eq. (7), i.e., as the average of two track TFs corresponding to Cast-iron braked wheels and Disc braked wheels.

4.2.2.1. Rail-pad stiffening. The default and extracted track TFs, which were used to implement a stiffening of rail-pads from soft (150 MN m^{-1}) to hard (1000 MN m^{-1}), are plotted in Fig. 9. An intermediate track TF, which represents “medium” rail-pads (500 MN m^{-1}), is also presented.

The default and extracted track TFs varied considerably with respect to each other both from quantitative and qualitative considerations. The default track TFs were larger in magnitude than the extracted TFs; see Fig. 9. The default and extracted track TFs also showed differences in the type of change caused by switching from soft to hard rail-pads. For the default TFs, this change caused an increase in magnitude at lower frequencies (around 160 Hz) and a decrease at higher frequencies (around 1000 Hz). On the other hand, the extracted TFs primarily decreased in magnitude with an exception at 250 Hz. The extracted TFs also highlighted a larger magnitude of change than the default TFs, especially when comparing the soft and medium rail-pads.

The significant difference between the default and extracted track TFs prevents them from being interchangeably used in CNOSSOS-EU. Therefore, the extracted TFs may be considered not as a supplement to the CNOSSOS-EU database, but rather as replacements to the default TFs. The ability of the *Updated* CNOSSOS-EU calculations to match the TWINS calculations (Figs. 6 and 7) confirms the accuracy of the extracted TFs over the default ones, thereby making them a better choice as input for CNOSSOS-EU. A possible cause for the unreliability of the default tracks TFs may be the unclear source of rail-pad stiffness values that are attributed to them (Kok and van Beek, 2019).

4.2.2.2. Installation of rail-dampers. In this case study, the installation of rail-dampers was a mitigation measure with two exceptions. First, it could not be implemented in the *Default* CNOSSOS-EU calculation due to limitations in the default database. Second, it was implemented in TWINS using an empirical ad-hoc modification of track decay rates which cannot be similarly implemented in CNOSSOS-EU (despite CNOSSOS-EU being the more empirical methodology of the two). The extracted track TF is compared with the baseline in Fig. 10.

The inclusion of a rail-damper reduced the magnitude of the track TF by at least 5 dB beginning from 630 Hz, and up to 13 dB at around 2000 Hz. The change brought about by this mitigation measure in the track decay rates (see Fig. 5) and in the extracted track TFs (see Fig. 10) is shown in Fig. 11. A negative correlation was observed between these two spectra, with a Pearson's coefficient of -0.75 and -0.74 for correlation with the vertical and lateral decay rates, respectively.

The correlation between the change in track TF (input to CNOSSOS-EU) and the change in track decay rates (input to TWINS) show that the former is able to capture the impact of installing rail-dampers when described through the latter. This may be the reason for the *Updated* calculation to match the TWINS calculation, given the average deviation of -0.8 dB (A) and $+0.3$ dB(A) between them for the absolute and relative metrics, respectively (Figs. 6 and 7).

The correlation between the track decay rates and the track TF may enable to estimate the impact of installing rail-dampers on any given track TF. This may allow for an ad-hoc modification of CNOSSOS-EU track TFs that incorporates the effect of rail-dampers, similar to the ad-hoc modification used in TWINS. However, the current case study cannot test this possibility due to the limited number of configurations with rail-dampers.

5. Conclusion

This contribution proposes an approach to improve the CNOSSOS-EU railway noise database by providing more specific and reliable vehicle and track transfer functions. These transfer functions are extracted using TWINS rolling noise calculations of the wheel, rail and sleeper components. The approach is tested by evaluating the impact that these extracted transfer functions have on the CNOSSOS-EU calculations in comparison to the default ones, taking calculations from TWINS as reference results.

A case study comprising rolling noise mitigation measures was defined. This allowed evaluating the potential of the extracted transfer functions in improving the CNOSSOS-EU calculations. These are shown to reduce the average deviation between CNOSSOS-EU and TWINS from 6.1 dB(A) to 0.8 dB(A) in terms of absolute rolling noise sound power levels. A decrease is also observed when estimating the reduction potential of different mitigation measures; the deviation reduces from 1.2 dB(A) to 0.3 dB(A). In addition to this, a current limitation of CNOSSOS-EU, wherein certain changes to train-track infrastructure (such as installing rail-dampers) could not be calculated, has been overcome by means of these extracted transfer functions.

Note that the assumed choice of the rail and wheel roughness did not affect the results of this study, since both TWINS and CNOSSOS-EU used the same input roughness. However, this assumption would have a significant influence when comparing rolling noise simulations (from CNOSSOS-EU or TWINS) with experimental measurements. Therefore, the choice of roughness would require more careful consideration when validating CNOSSOS-EU with measurements.

This approach shows potential to improve CNOSSOS-EU railway noise evaluation by providing more accurate alternatives to the existing transfer functions in the default database. It can also expand the specificity and the range of train-track infrastructures that the default database can represent. This allows CNOSSOS-EU to estimate the railway noise component of strategic noise maps more accurately. This can subsequently lead to the preparation of more realistic noise management actions plans, as well as a more reliable assessment of the harmful effects of railway noise on the population.

The application and effectiveness of this approach is strongly dependent on TWINS. Implementing this approach requires the availability of TWINS calculations. However, the transfer functions extracted from a TWINS calculation may be appended to the CNOSSOS-EU database once and for all. The dependence of this approach on TWINS also enforces certain limitations. The extended infrastructures, which CNOSSOS-EU can represent, are constrained to the infrastructures considered by the TWINS calculations. Furthermore, the resulting accuracy becomes inherently linked to the accuracy of TWINS calculations.

An improved CNOSSOS-EU railway noise evaluation increases the benefit of fulfilling the END 2002 requirement of making strategic noise maps. The presented approach may improve the quality and size of the existing database of CNOSSOS-EU transfer functions. In line with the motivation behind a common noise assessment method in Europe, it may therefore be beneficial to share the extracted transfer functions across the different Member States through a common online repository. This would enable all actors to benefit from a more reliable application of CNOSSOS-EU.

CRediT authorship contribution statement

Siddharth Venkataraman: Conceptualization, Methodology, Software, Validation, Formal Analysis, Investigation, Data Curation, Writing - Original Draft, Visualization. **Romain Rumpler:** Conceptualization, Writing - Review & Editing, Supervision, Funding acquisition. **Siv Leth:** Conceptualization, Resources, Writing - Review & Editing, Supervision, **Martin Toward:** Software, Validation, Investigation, Resources **Tohmmy Bustad:** Resources, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could appear to influence the work reported in this paper.

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